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Climate and Managing Corn-Soybean Agroecosystems 2: Findings, Implications and Recommendations

Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems

CLIMATE AND MANAGING CORN-SOYBEAN AGROECOSYSTEMS 2

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Findings, Implications and Recommendations

Technical Report Series:
Findings and Recommendations of the
Climate and Corn-Based Cropping Systems
Coordinated Agricultural Project

Volume 2 of 5

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Technical Report Series:
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Agriculture's most complex and difficult task is to effectively manage row-crop agroecosystems to optimize yield while also protecting and enhancing natural resources, insuring rural livelihoods, and meeting national and world food security challenges. The changes in climate on a local and global scale require agriculture to accelerate systems-level approaches and solutions that integrate across the environment (E), crop genetics (G), and management (M). Responding to and managing for this complex interaction, E x M x G, is the challenge facing farmers, advisors, scientists, agencies, and policy makers.

Upper Midwest food, feed, fiber, and fuel are produced under environmental, market, and social conditions that are dynamic and unpredictable—sources of both opportunity and potential disaster. Further complicating management decision-making is that research-based recommendations are not always able to be extrapolated more than a few miles because of spatial variability in weather and climate, soil, land cover and topographical conditions. This means intensive agricultural research is critical to ensure resilience and long-term vitality of the farm enterprise. Farmers, scientists, and agencies must work collaboratively to reduce the risk to farm economies and environmental health while increasing the benefits gained from row-crop agriculture.

The USDA-NIFA Sustainable Corn CAP project has been researching this complexity and evaluating solutions for sustainable crop adaptation to variable and changing weather patterns. The team has studied the impacts that farmers' decisions and a variety of management practices have on the carbon, nitrogen, and water footprints of Midwest corn-based cropping systems. These management practices, often integrated at the field level, include controlled drainage, cover crops, reduced tillage, nitrogen sensing, and diversified crop rotations.

The synthesis of disciplinary sciences drawn from field experiments and models in conjunction with the knowledge and experiences of cooperating farmers has enabled the team to evaluate a suite of adaptive solutions. The overarching criteria used to guide the viability of solutions were continued productivity for U.S. farmers and minimization of unintended consequences on the natural environment. This technical report, *Climate and Managing Corn-Soybean Agroecosystems 2: Findings, Implications and Recommendations*, is the second volume of research-based outcomes from the Sustainable Corn CAP project. This report highlights additional key results not published in Volume 1.

The integration of the team's biophysical and social sciences in current and future climate scenarios are woven throughout this volume. The outcomes from one discipline inform and build on the work of others to produce robust recommendations toward systems management.

The findings, implications, and recommendations highlighted on the following page are for cover crops and serve as an example of the integration found in this report for other management practices across carbon, nitrogen, and water.

The following are excerpts from the full report representing the trade-offs related to the addition of a cereal rye cover crop into the suite of farmers' management practices.

- Current cultivars and management practices under projected future temperature increases of 2˚ C or more are likely to lead to corn yield declines of 33% on average over the Midwest. The predicted decline in yields do not account for the potential inclusion of adaptive on-farm management practices to changing conditions.

- Improved management practices such as cover crops can partially offset the projected yield decline in future climate scenarios associated with increased temperature and changes in precipitation patterns, but these practices are not sufficient to reverse the effects.

- In a climate model-based scenario, one-third to one-half of a random sample of Corn Belt grain farmers indicated they would increase their use of cover crops, no-till and/or tile drainage to adapt to changes in climate.

- There are potential maladaptive properties associated with the use of cover crops, no-till and tile drainage. For example, a potential increase in herbicide use may occur with cover crops.

- A winter rye cover crop has shown benefits in terms of water and soil conservation and reduced nitrous oxide (N_2O). However, management is a critical factor in maximizing benefits and minimizing negative cash crop impacts. For example, poor corn establishment and yield can occur if timing of cover crop termination is too late.

- Iowa commercial farms where corn was planted following a rye cover crop had greater presence of and feeding injury to corn by the true armyworm, an early season insect pest, compared to corn fields that did not plant a cereal rye cover crop.

- Model-based life cycle assessment has identified a winter rye cover crop added to the corn-soybean rotation provides substantial life-cycle improvements in water quality and reduces soil loss per ton of corn, but increases total fossil energy use and has variable impacts on life-cycle emission of climate forcing gasses.

- Greater benefits of cover crops could occur under future climate conditions in reducing nitrogen losses to streams and proximate water bodies.

- Although cover crops are known to add additional carbon back to the soil, this is a long-term investment. Based on project experiments, more than four years of cereal rye cover crops are necessary before a significant increase in soil organic carbon becomes measurable.

- Farmers' uncertainty about projected climate change impacts on their production systems is influenced by their beliefs about climate change, experiences with drought, concern about heat stress on crops, and agricultural information networks. Outreach and engagement efforts to increase willingness to adapt will need to be tailored to each farmer's unique situation.

- Development of expanded cost sharing programs and other approaches are recommended to reduce cover crop costs for producers and encourage greater cover crop adoption on-farm.

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CLIMATE AND MANAGING CORN-SOYBEAN AGROECOSYSTEMS 2

Findings, Implications and Recommendations

SECTION 1. INTRODUCTION

Ninety-four million acres of land in the United States were planted to corn in 2016 with most grown in the upper Midwest. The Midwest soils and climate make it among one of the highest producing corn-soybean regions in the world, with 10-20 percent of its crop exported annually. According to USDA, the U.S. 2016 corn crop of over 15.1 billion bushels surpassed the previous record of 14.2 billion bushels set in 2014. Midwestern states have set yield records over the past few years with Minnesota producing a record 193 bu/ac, Indiana 173 bu/ac, Illinois 197 bu/ac, and Iowa 203 bu/ac in 2016. That statewide yield for Iowa is an all-time record for any major corn producing state in the United States.

Midwest agriculture also is one of the major exporters of sediment and nitrogen (N) that contributes to decreasing water quality in the region, with impacts on the Great Lakes and Mississippi and Ohio rivers, their tributaries and downstream. In 2013, the hypoxia zone in the Gulf of Mexico covered about 5,800 square miles, which is larger than Connecticut. The National Oceanic and Atmospheric Administration (NOAA) estimates harmful algae blooms that lead to hypoxic conditions in U.S. marine waters cost on average $82 million annually due to impacts on public health, tourism and the seafood industry. The governor of Ohio in 2014 declared a state of emergency as the city of Toledo issued a “do not drink/do not boil the water” notice to over 400,000 residents, due to toxins from blue-green (cyanobacteria) algae blooms. These blooms were caused in part by N and phosphorus (P) in western Lake Erie, the city’s drinking water source. Land use, water flow modifications, increased nutrient loadings including N and other pollutants, food web alterations, and a changing climate all have been implicated as causal agents for the changes in our river, lake, and ocean ecosystems (NOAA 2016).

Day-to-day weather variability and longer-term shifts in weather patterns and climate directly and indirectly affect United States agricultural productivity and the agroecosystems associated with crop production. The productivity and environmental impacts of the corn-soybean system are strongly influenced by the timing and extreme variations in temperature, precipitation, wind and humidity throughout the growing season. Local weather conditions – historical, current and forecast – affect a myriad of farm decisions: selection of crop and seed variety; timing of planting, fertilization and harvest; disease and weed control; water management; crop rotations and tillage practices (Klemm and McPherson 2017). Changes in the Midwest climate have lengthened the growing season by almost two weeks since 1950. This is due in large part to earlier occurrence of the last spring freeze (Pryor et al. 2014). Continued, small, long-term average temperature increases are projected to shorten the duration of corn reproductive development with potential future yield declines. Abundant precipitation during the growing

season in recent years has produced high crop yields, despite some farmers experiencing significant delays in spring planting because of saturated soils early in the spring. However, increases in extreme precipitation events have increased the volume and speed of runoff water, accelerated rates of soil erosion, and led to high levels of off-field, off-farm N and sediment losses into nearby waters.

Weather and climate impacts on regional and local corn-based systems and their agroecosystems in the Midwest have been the focus of the biophysical and social-economic research conducted by the USDA-National Food and Agriculture Institute (NIFA) Climate and Corn-based Cropping Systems Coordinated Agricultural Project (CAP) (aka Sustainable Corn CAP) team (2011-2017). The intent of the project was to better understand how management practices in corn-based systems affect N, carbon (C) and water cycles under variable weather and climate, and to identify strategies that have the potential for implementation by farmers and industry with support through policy. This volume, *Climate and Managing Corn-Soybean Agroecosystems 2: Findings, Implications and Recommendations* (Vol 2 of 5), along with Volume 1, *Climate and Managing Corn-Soybean Agroecosystems 1: Findings, Implications and Recommendations* (Vol 1 of 5), present key findings and recommendations from the research conducted by the Sustainable Corn CAP team.

1.1 SYNTHESIS AND INTEGRATION OF SCIENCES

Interdisciplinary and multidisciplinary research are crucial to advance agricultural sciences and address complex societal challenges related to the sustainable production of food, feed, fuel and fiber under increasingly variable weather and a changing climate. Research on carbon (C), nitrogen (N) and water cycles in corn-based systems provides new knowledge, valuable insight and guidance for improving the management of these systems to create more resilient agroecosystems. A resilient agroecosystem has the ability to absorb disturbances to the system – such as high precipitation, growing season drought, or new patterns of consistently above normal temperatures – and still retain its basic function and structure. Basic functions and structure of the corn-based agroecosystem encompass yield productivity, retention and enhancement of soil organic C (SOC), water availability for plant growth, protection of water resources, N and other nutrients retained on-field and on-farm for plant consumption, and not lost to the atmosphere as N_2O or to proximate water bodies that can degrade local and downstream water conditions.

The Sustainable Corn CAP was a multi-pronged research, extension and education initiative consisting of a central database; field and landscape level crop experiments using standardized protocols for core measurements; primary and secondary social and economic data; and historical, current and forecast climate data from experimental sites and the region.

In Volumes 1 and 2, site specific and system-scale project data have been synthesized and integrated to inform the challenge of climate change adaptation for upper Midwest agricultural systems. The research includes not only the biophysical findings pertaining to grain yield, C, N and water cycles, but also the social science findings on the views and practices of farmers who are managing the landscape and seeking ways to adapt to changing conditions while assuring productivity and protecting the agroecosystem.

An integrated research approach across experimental field site locations captured crop and environmental responses under a suite of management practices. Within these different practices, team scientists measured carbon, nitrogen, greenhouse gas, water quality and flow, pest populations and agronomic indicators.

A set of local, regional and national scale models utilized the field research data to examine current and predicted implications of the various practices on C, N and water under different climate conditions. Additionally, farmer social and economic behaviors and responses to changing climate and weather were integrated to identify practices most likely to be implemented.

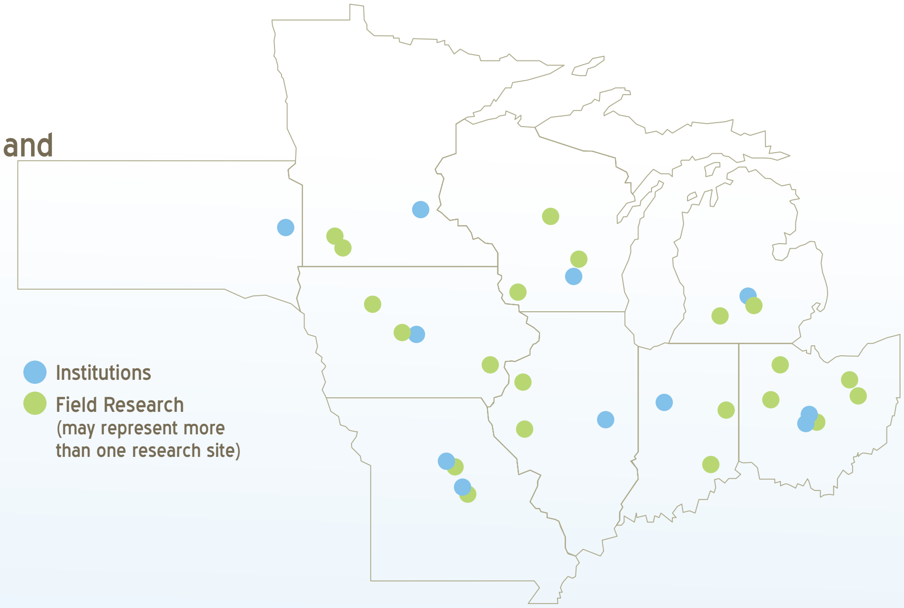
1.2 BIOPHYSICAL AND SOCIAL-ECONOMIC RESEARCH DATA COLLECTED

Volume 1 (pages 2 to 9) contains a full description of the Sustainable Corn CAP team's methods, experimental design, biophysical and social-economic research data collected, spatial coverage and USDA National Agricultural Statistics Service (NASS) acreage and production data for corn, soybean and wheat. A summary is provided here of the research scope.

An expansive field research network of 35 sites comprised the biophysical research network with sites in all project states except South Dakota (Figure 1 and Appendix B). This network combined previously existing research sites with newly established sites to comprehensively address the team's research agenda.

The team selected management practices widely used by farmers as well as comparative practices that were relatively novel or not yet widely implemented across the landscape. Management practices were studied to determine adaptation and mitigation capacity relative to climate change, and to measure overall productivity and sustainability indicators. Management practices investigated include corn-soybean rotation; cover crops (cereal rye in particular) within a corn-soybean rotation;

FIGURE 1 | Location of Sustainable Corn CAP participating institutions and field research sites.



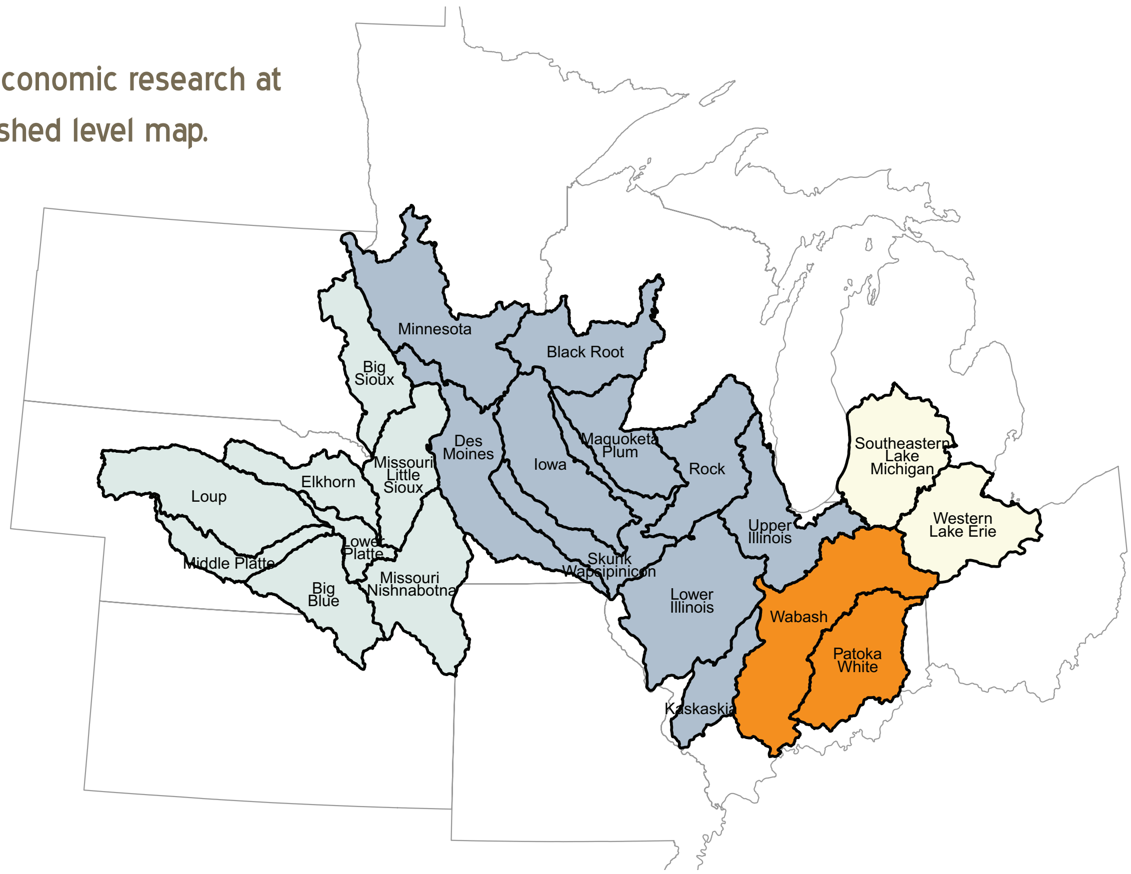
extended and diverse crop rotations; organic cropping system; drainage water management; canopy N sensing; and tillage management (no-till and conventional). Refer to Volume 1 Appendix D for a complete listing of management practices associated with each field site.

Most research sites began collecting data in 2011 and measured parameters for five years through the 2015 growing season. Project scientists collected data using standardized protocols developed by the team prior to the first field season (Kladivko et al. 2014). Refer to Volume 1 Appendix E for a detailed list of data collected by the team that spans crop, soil, water, greenhouse gas (GHG) and pest measurements. Research data were uploaded to the team's central database by team members with review and quality control performed by database managers to ensure data integrity and adherence to standardization with iterative exchanges often occurring (Herzmann et al. 2014).

The team's social-economic research focused on an understanding of Corn Belt farmers' perspectives on climate change and potential adaptation and mitigation strategies. Primary data were collected using a mixed methods approach: a major random sample survey, conducted in partnership with the USDA-NIFA funded Useful to Usable project, of 4,778 farmers across 11 Upper Midwest Corn Belt states (Figure 2), plus in-depth interviews and pre-post surveys with a select group of farmer cooperators. The 2012 random sample survey, which was stratified by 22 HUC 6 (Hydrological Unit Code) watersheds, drew its sample from the USDA NASS Census of Agriculture master list of farmers. To date, this remains the largest scientifically rigorous survey focused on farmers and climate change. Refer to Volume 1, pages 8-9, for more information pertaining to this farmer survey.

The second major social science research component consisted of in-depth interviews with 159 farmer-cooperators recruited from the Sustainable Corn CAP extension educators' networks. The interview process consisted of two parts: a longitudinal survey (baseline 2012 and follow-up 2015), and in-depth interviews in 2013 with the 159 cooperating farmers.

FIGURE 2 | Social economic research at the HUC 6 watershed level map.



SECTION 2. FINDINGS, IMPLICATIONS, RECOMMENDATIONS

Research conducted at individual experimental sites provided data that are the basis of findings and recommendations developed for that location and those similar to it. Each experimental study is essentially a case study that is locale and temporally specific. Thus, site specific findings may or may not be directly applicable to a wider geographic region due to differences in topography, soils, spatial location and weather, as well as farm management approaches. Regional syntheses and modeling enable the scaling up of these findings to a broader expanse of the landscape by identifying commonalities and expected responses. Modeling with climate projections enabled the prediction of how management practices might perform in the future under different climate and weather scenarios and the impacts on the landscape. The integration of field experiments, social-economic findings, climate data and modeling were used to produce systems-level recommendations for current and future production scenarios. Findings derived from modeling are noted in the report as follows:

Finding based on modeling

2.1 CLIMATE CHANGE AND THE UPPER MIDWEST

The Midwest during the last century has seen an increase in extreme rainfall events and flooding, increased heat wave intensity and frequency, and increased humidity (Pryor et al. 2014). The 3rd National Climate assessment documents longer growing seasons for the Midwest and rising carbon dioxide levels that have increased the yields of some crops, but projects these benefits are likely to be progressively offset by extreme weather events. Heat waves during pollination are threats to corn and soybean yields; and wetter springs can lead to farmers changing to late-planted shorter-season varieties with potential impacts on yields. These trends have increased risks of soil erosion, declining water quality, degraded air quality and increases in harmful blooms of algae, especially in the Great Lakes. The weather and climate of the Midwest are the context and drivers of project findings that are reported in the following sections.

2.1.1 Model performance under future climate

Complex agroecosystem models, such as those used to simulate crop yield and the environmental impacts of crop production, are based on assumptions from prior literature and past experiments when data are available. These models may inaccurately predict crop system and ecosystem performance under future climate if representative experimental data are not available to calibrate and test the models. In the Sustainable Corn CAP, field experiments were used to improve model assumptions and subsequently, the accuracy and robustness of model output across the range of climatic conditions of the prediction period. Experimental data gathered from controlled field experiments are valuable in ground truthing model assumptions and are critical for model calibration. However, despite experimental field data, model assumptions may not account for how farm management decisions in aggregate under different conditions will affect the larger landscape.

Finding based on modeling: The use of more than one General Circulation Model (GCM) showed the choice of GCM can lead to substantially different outcomes when climate change information from GCMs is used for watershed basin modeling. The research captured the range of precipitation and temperature results from GCMs that were included in phase 3 of the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project (CMIP3; PCMDI, 2007). Refer to Appendix 3.1 for a description of the GCMs used (Panagopoulos et al, 2015).

Implication: The use of a single GCM can produce misleading results when climate change information from GCMs is used for analysis of possible future climate impacts on Corn Belt agricultural production, including assessment of how the uncertainties in climate change projections feed through to uncertainties in outcomes for agriculture and water. Multiple GCMs provide a basis for a more comprehensive and robust analysis, including quantification of uncertainties.

Recommendation: Multiple GCMs, sampling the full range of projected possible future climates for mid-century (2046 to 2065) and other future time periods, should be used when performing analyses of possible future climate impacts on Corn Belt crop production and corresponding best management practices (BMP) and/or cropping system effects.

2.1.2 Translation of experienced weather and climate data to decisions

Climate scientists rely on observed historical weather and climate data to inform current and future climate model projections. Similarly, agricultural producers use historical events—recent past experiences and historical narratives—to construct local knowledge to assess, quantify and manage current and future risks. These historical data, events and experiences become reference points or analogs when compared to a current phenomenon that exhibits similar characteristics specific to past conditions.

Finding: In-person interviews with Corn Belt farmers reveal past experiences and decisions influence farmers' perceptions of current and future risks, and are used to integrate scientific climate information to inform decision-making (Wilke and Morton 2017).

Finding: Intergenerational narratives and experiences with recent past extreme weather events often become analog years used as benchmarks by farmers to build knowledge about effects of weather and climate shifts, and to guide current and future decisions (Wilke and Morton 2017).

Implication: Decision-making is a continuous social learning process where information from past experiences, personal and intergenerational knowledge, and personal values are synthesized and used as input, when relevant to current decisions.

Recommendation: Encourage farmers to use a performance-based management approach that measures, monitors and evaluates historical data on crops, management practices and weather to assess impacts on yields, loss and gain of soil C stocks and other outcomes. Tracking long-term changes in field and farm outcomes, along with local weather, can reduce inaccuracies associated with long-term memory of events.

Weather station in field plot at Purdue University.

Recommendation: Climate science communication and outreach efforts to farmer audiences can be improved when future climate model scenarios are placed in the context of past weather and climate events that have affected agriculture. Including a past timescale that includes recognizable climatic events important to farmers provides personal associations with the data presented, and offers a context for evaluating potential impacts of future scenarios.

Finding: A random sample survey showed the majority (65%) of 4,496 farmers in the upper Midwest agreed or strongly agreed there was too much uncertainty about the impacts of climate to justify changing their agricultural practices and strategies. Farmers' uncertainty about projected climate change impacts on their production systems is influenced by their beliefs about climate change, experiences with drought, concern about heat stress on crops, and agricultural information networks (Morton et al. 2017).

Implication: This finding suggests a combination of insufficient information and normative influences on climate beliefs are influencing farmer uncertainty.

Recommendation: In cases where uncertainty is caused by insufficient information, improved farmer access to and use of historical crop and local climate records, as well as decision support tools that simulate different climate scenarios and their impacts on production, could improve estimates of future risks. However, more information may be insufficient to address claims of uncertainty when differing political and cultural norms contest the parameters of climate change. This suggests scientific knowledge must be linked to social values and beliefs and trusted agricultural networks for widespread adaptive management to a changing climate to occur.

Finding: Past research (Arbuckle et al. 2014) employed latent class analysis of characteristics that are not directly observable (e.g., climate change beliefs, risk perceptions) to identify six classes of farmers with different perspectives on climate change, and recommended communication might be tailored to segments of farmer audiences. Further research (Arbuckle et al. 2017) compared the six classes of farmers using observable characteristics such as farm type, land management practices, and farmer demographics and found insufficient systematic, meaningful patterns of difference in those observable characteristics to guide or justify audience segmentation. In other words, farmers who believed anthropogenic climate change is occurring, that it poses risks to agriculture, and that adaptive action should be taken, were not substantively different in terms of observable characteristics such as farm size, farm characteristics, and farmer demographics from farmers who denied the existence of climate change.

Recommendation: Any climate change engagement efforts by University Extension and other agricultural stakeholders should (1) use caution when looking to observable characteristics to facilitate audience segmentation, and (2) work to develop outreach materials that appeal to broad farmer audiences.

Michigan State University Extension field day.

Finding: Farmers who reported greater concern about climate change and who were more supportive of adaptive action also tended to report their agricultural decisions were more influenced by key agricultural actors such as University Extension and soil and water conservation agencies. Farmers who were less concerned about climate change and who tended not to support adaptive action (between one-third and one-half of farmer survey respondents) tended to be less influenced by key actors in agricultural social networks (Arbuckle et al. 2017).

Implication and Recommendation: Extension and other stakeholder groups that work with farmers should seek to expand their outreach and programming efforts to engage farmers who are not already within their spheres of influence.

Finding: In a climate model-based scenario, one-third to one-half of a random sample of Corn Belt grain farmers indicated they would increase their use of cover crops, no-till and tile drainage to adapt to projected climate changes (Roesch-McNally et al. 2016).

Finding: Among Corn Belt farmers who indicated they would increase their use of cover crops, no-till and tile drainage in response to predicted climate changes, positive attitudes towards climate change adaptation, and higher levels of perceived risks associated with climate change were positive predictors of intentions to increase their use of the practices. Confidence in the adequacy of current practices was a negative predictor of intention to adapt (Roesch-McNally et al. 2016).

Finding: Farmers who placed higher importance on visiting other farmers to learn from their practices and strategies, as well as farmers who were already using cover crops, no-till, or tile drainage, were more likely to report intentions to increase use of the practices to adapt to predicted climate changes (Roesch-McNally et al. 2016).

Observation: There are potential maladaptive properties associated with the use of cover crops, NT and tile drainage. For example, a potential increase in herbicide use may occur with cover crops. Or increased short-circuiting of nitrate-N to streams may occur due to tile drainage systems compared to non-tiled fields. Since farmers likely will increase use of all of these practices, research should continue to document the potential positive and negative impacts associated with these adaptive strategies at the field and landscape scale.

Implication and Recommendation: While some Corn Belt grain farmers indicated they would increase use of key adaptive management practices in response to a changing climate, many others expressed they would not. This suggests different outreach and engagement on adaptation strategies will be needed to increase willingness to adapt.


Iowa State University Extension field day.

Implication and Recommendation: Findings also highlight the importance of farmer networks in expanding the use and adoption of adaptive strategies, suggesting development of robust farmer networks that include farmer exchanges around scientific findings, and opportunities to observe and experiment with practices, will be important for increasing adaptation actions.

A synthesis of key findings from Corn Belt farmer surveys and in-depth interviews has expanded our understanding of Corn Belt farmers' perspectives on climate change, their responses to extreme weather events and their attitudes towards adaptation and mitigation. This aggregation of other findings resulted in a series of recommendations for scientists, Extension and land managers to communicate and engage farmers and their crop advisors with Extension and land managers on the topic of climate change (See Volume 3 in this series for more detail, Morton et al. 2016 and Roesch-McNally et al. In Review).

Recommendation: When working directly with farmers, focus the discussion on reducing weather-related risks to their operation associated with more extreme and variable weather, rather than 'climate change.'

Recommendation: Encourage farmers to identify actions they can take to adapt to more extreme and variable weather on their farms.

Recommendation: Farmers are problem solvers who are concerned about soil and water resources upon which the future of their farm operation depends. Explore soil and water conservation strategies as ways to purposefully reduce off farm N, other nutrients and soil losses; and link to future productivity and water quality concerns.

Recommendation: Work closely with scientists to develop continuous communication feedback loops among scientific findings, local knowledge and experiences to improve information exchanges.

2.2 CORN AND SOYBEAN PRODUCTION AND MANAGEMENT

The majority of U.S. corn and soybean production occurs in the nine-state region of the upper Midwest, where the Sustainable Corn CAP project was conducted. The dominant cropping system in this region has been an annual rotation of corn and soybean. For the past five years, 60 million acres (24 million hectares) of corn and 50 million acres (20 million hectares) of soybean have been grown in this region. Refer to Volume 1 for state-level production data and trends.

2.2.1 Crop yield in future climate

The following results are based on model simulations using current management practices and genetics (i.e. cultivars) for the Midwest. Projecting crop yields in the future requires the use of existing biophysical data available from this project and other sources such as USDA National Agricultural Statistics Service and an expectation of how land will be managed in the future. There are many variables that can change model projections and accuracy, such as shifts in management practices at the farm and watershed levels. Social science research from this team has shown farmers' willingness to change the way they farm when they identify a problem exists with current practices. The findings, implications and recommendations presented here largely represent the biophysical and climate constraints in the future.

Finding based on modeling: Under projected future climate and with current cultivars and management practices, corn yield is expected to decline on average over the Midwest by 33%, but yield increases are predicted for states like Michigan (+27%) and Wisconsin (+9%). The decline in predicted yield is associated with temperature increases by 2˚ C or more in the future while retaining current management practices and crop genetics; these do not consider adaptation practices (Basso et al. 2015).

Implication: Improved management practices such as the addition of manure, cover crops, extended and diversified crop rotations, springtime or split applications of N fertilizer and no-till can partially offset the projected yield decline in future climate scenarios associated with increased temperature and changes in precipitation patterns, but these practices are not sufficient to reverse the effects. New cultivars along with best management practices will need to be introduced to adapt to changing climate conditions.

← Farmer harvesting corn and unloading grain for transport to on-farm storage

Finding based on modeling: Temperature increases resulting from a changing climate are the main factor in corn yield declines many decades into the future. These yield declines are not offset directly by the use of a cereal rye cover crop.

Implication: A cereal rye cover crop has shown benefits in terms of water and soil conservation and reduced nitrous oxide (N_2O) emissions, but it is crucial that management is implemented to maximize benefits and minimize losses. For example, poor corn establishment and yield can occur if timing of cover crop termination is too late.

Finding based on modeling: Model-based life cycle assessment indicates that including a cereal rye cover crop in the corn-soybean rotation provides substantial life-cycle improvements in water quality and reduces soil loss per ton of corn, but increases total fossil energy use and has variable impacts on life-cycle emission of climate forcing gasses.

Implication: Under predicted future climate, life-cycle impacts in all categories are likely to increase per ton of corn despite the presence of a winter rye cover crop in the corn-soybean rotation.

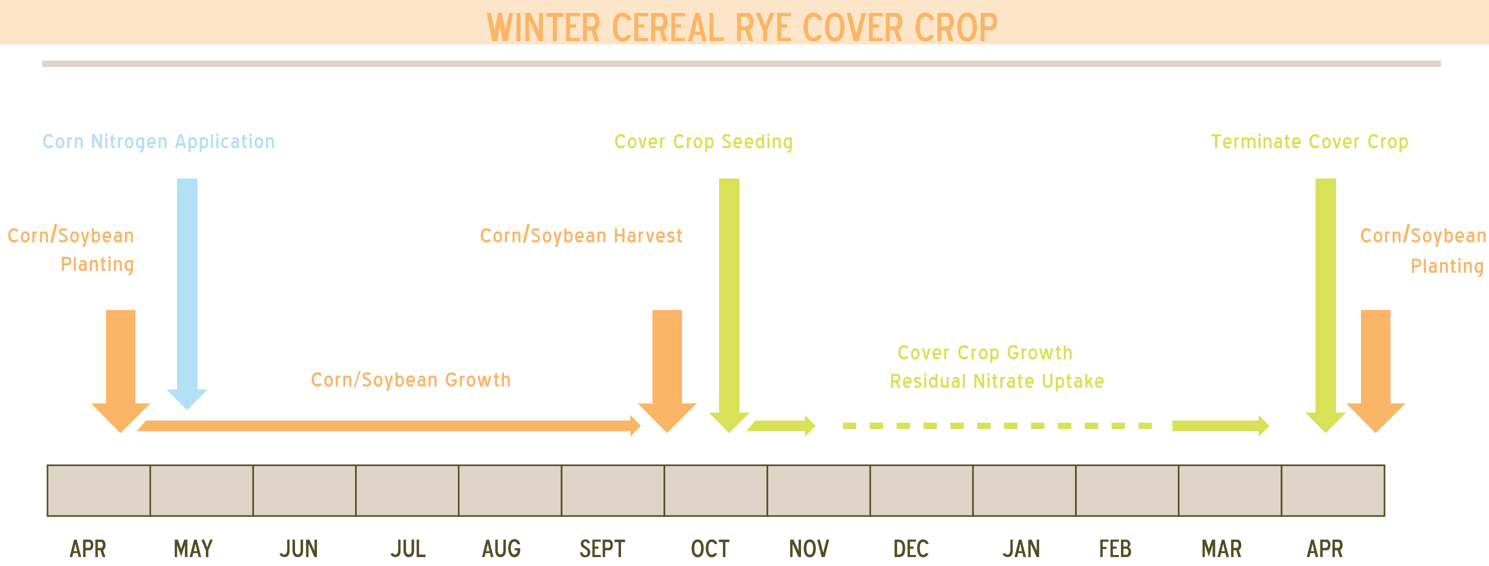
2.2.2 Management practices for yield stabilization or optimization

Each year, farmers modify their management practices in an effort to provide the most hospitable environment for the crop, given their knowledge and financial capital. Management practices differ in complexity for a farmer to implement due to their investments in equipment, changing price structures of seed and fertilizer inputs, and weather variations that may limit the use of certain practices or field work operations from occurring. Management practices noted in this section are specifically focused on crops grown, tillage used and the integration of cover crops into existing crop rotations.

The reduction in tillage so the field is managed with either "reduced tillage" or "no-till" has the potential to substantially decrease soil loss, but these practices can be a challenge for some farmers to establish in certain areas of the Corn Belt.

Finding: Crop yield stability was greatest in no-till management compared to conventional tillage at a selection of research sites in the Corn Belt during 2009 through 2013.

FIGURE 3 | Timeline for planting, growing and terminating a winter cereal rye cover crop



Implication: No-till management may be used to stabilize yields annually as affected by weather variability and spatial land variability across the Corn Belt. No-till management can help retain soil from erosion loss, which has long-term benefits.

Diversification of the predominant cropping system to include a third crop can be a powerful tool for farmers to reduce economic risk, disrupt pest cycles, increase soil resilience and improve water quality. However, the type of crop (grass or legume, annual or perennial) as well as the type of production practices surrounding the crop determines the ultimate impact, whether positive or negative, on the soil and water.

Finding: Continuous corn yielded 0 to 20% less than corn rotated with soybean in Wisconsin and an average of 15-20% less in Illinois. Corn in the corn-soybean-wheat rotation yielded 5 to 10% more than corn in corn-soybean in Wisconsin, except for the northernmost location that is similar to findings in Illinois where corn has yielded about 5% more.

Implication: Corn grown in a rotation consistently yields more than corn grown in repeated monoculture. This finding holds for differing environments as results were consistent across Wisconsin and Illinois sites. Farmers can maximize corn yields by rotating with soybean, and more by adding wheat into the rotation.

Finding based on modeling: Adoption of cover crops across 95% of the cropland (80,000,000 ac or 32,000,000 ha) in the Upper Mississippi River Basin (UMRB) and Ohio-Tennessee River Basin (OTRB) could result in a cost of reducing N of $15 to $37 per lb ($7 to $17/kg) and P of $187 to $493 per lb ($85 to $224/kg) based on the total cost divided by the total N loads or total P loads (Kling et al. 2014). The N and P loads were estimated via simulations performed with the Soil and Water Assessment Tool (SWAT) model. This assumes cover crop costs range from $25/ac to $35/ac ($61.8/ha to $86.6/ha) based on data reported in the Iowa Nutrient Reduction Strategy and other sources.

Implication: Development of expanded cost sharing programs and other approaches are recommended to reduce cover crop costs for producers and encourage greater cover crop adoption by producers in their field operations.

Finding: Focus groups with Iowa farmers identified challenges to cover crop adoption including both in-field barriers and structural barriers (e.g., markets, infrastructure) that constrain their inclination and ability to integrate cover crops into their production systems (Roesch-McNally et al. 2017). See Figure 3 for a visual display of the management timing with cover crops.

Finding: Farmers have found creative ways to overcome in-field and structural barriers to successfully integrate cover crops into their cropping systems. Successful adopters were found to have implemented a "whole systems" approach to cover crops management, in which they prioritize the success of their cover crops by focusing on multiple aspects of management, including changes they have made to nutrient application and modifications to equipment. Farmer-to-farmer networks were found to be important factors in reducing barriers and facilitating adoption of cover crops (Roesch-McNally et al. 2017).

Finding: Focus group participants emphasized the importance of diversified cropping systems and livestock in helping farmers adopt cover crops across a wider expanse of land in production (Roesch-McNally et al. 2017).

Implication: Attention must be paid to structural constraints to cover crop adoption for this practice to become more widespread. This might include reducing barriers by creating markets and other incentives for more diversified agriculture in the Corn Belt and opportunities for livestock and crop integration. Further facilitation of farmer-to-farmer networks will help farmers experiment and adopt cover crops in their operations through a trial and error approach and share their results with others.

2.3 INTEGRATED PEST MANAGEMENT

A changing climate impacts Midwest temperature, precipitation, humidity and other weather variables; and is expected to continue influencing abundance and reproduction rates of pest populations and migration patterns. The term "pest" encompasses diseases, weeds, insects, and animals that can destroy or damage a crop. Integrated pest management (IPM) is a systems approach to managing pests that integrates practices including regular monitoring with intent to control pests with chemical, mechanical, and biotic mechanisms to reduce crop damage, economic losses and environmental impacts. Micro-climates and local weather variability (e.g. temperatures, high precipitation, drought, and high relative humidity) in conjunction with crop development influence the timing and rates of pest migration and reproduction of plant pathogens, weeds, and insects. Some of the environmental variables that affect pest pressure include:

- Longer growing season (shifted frost dates)
- Warmer winters
- Warmer nighttime temperature
- More frequent severe precipitation events
- Increased atmospheric humidity

Finding: Observations from the 1950s through the present show increasing atmospheric humidity in the upper Midwest, especially since 1980.

Recommendation: The potential for increased humidity to exacerbate pest and disease pressure needs more in-depth research so recommendations for adaptive measures can be devised.

Finding: Iowa commercial farms where corn was planted following a cereal rye cover crop had significantly greater presence of and feeding injury to corn attributed to the true armyworm, an early season insect pest of corn, compared to cornfields that did not plant a rye cover crop (Dunbar et al. 2016 b).

Recommendation: Although true armyworm is more common in fields planted to corn following a cereal rye cover crop, significant feeding injury to corn remains sporadic but possible. Therefore, farmers should scout for feeding injury and true armyworm larvae from corn emergence through the eighth leaf (V8) developmental stage.

Implication: Several species of pest insects migrate during the spring. Field or crop attractiveness, scouting technique and pest management practices vary by pest species of insect. Some species may be limited to the field edge, like common stalk borer, whereas others may colonize the entire field if it is attractive, like true armyworm.

Implication: At present, there are no seed treatments or genetically modified corn hybrids labeled for true armyworm management. Foliar-applied insecticides are labeled for and effective, however, the need for an application of insecticide for management of true armyworm should be based on scouting and economic thresholds. Prophylactic uses of foliar-applied insecticides are not cost effective, as populations are sporadic.

Recommendation: Farmers planting cereal rye cover crops should focus their scouting and pest management efforts on fields planted to corn following the cover crop. Early termination of the cereal rye cover crop can reduce the risk of injury to corn from early season pest insects and diseases, however, weather and field conditions may hinder efforts to terminate the cover crop when necessary.

Graduate student Mike Dunbar, Iowa State University, collects beneficial and pest insect data in extended crop rotations that include wheat.

Implication: Education on early season pest management is important to successful production, especially when using cover crops and/or no-till.

Recommendation: Cover crop adoption policy should include consideration of increased pest management costs.

Finding: Ground-dwelling, beneficial arthropod communities and individual taxa did not differ among three cropping systems: continuous corn, 2-yr annual rotation of corn and soybean, and a 3-yr annual rotation of corn, soybean and wheat. These experiments were conducted in long-term rotation plots in Illinois and Wisconsin (Dunbar et al. 2016 a).

Implication: All crops noted above in the cropping systems are annual crops and associated with agricultural practices that make infield habitat subject to anthropogenic disturbances and temporally unstable. Habitat instability and disturbance can limit the effectiveness and retention of beneficial arthropods, including natural enemies, granivores and detritivores.

Recommendation: Farmers wanting to enhance the beneficial arthropod communities within their fields should consider increasing non-crop and perennial species within landscapes in conjunction with more diverse rotation schemes.

2.4 WATER CYCLE

Climate and weather are drivers of the water cycle. All parts of agricultural watersheds are connected at multiple temporal and spatial scales by flows of surface and ground water, transport and transformation of physical and chemical materials and movement of organisms (USEPA 2015). The incremental effects of artificial tile lines, ditches and channels, individual streams and wetlands are cumulative across entire watersheds and must be evaluated in that context.

The use of water by crops varies during the growing season based on the development stage, with specific stages highly sensitive to limitations or excess water. The availability of water during the growing season is necessary for achieving high grain yields, but the need for water to be drained away to reduce ponding and saturated soils is equally important in many areas of the upper Midwest. The role of subsurface drainage systems is to drain water, providing trafficable conditions for field work and proper soil conditions for crop growth.

Interactions among land use, vegetative cover and the timing, rate and duration of water delivered by precipitation affect soil moisture, sediment transport and runoff. Downstream waters are the time-integrated result of all waters contributing to them. Thus, aggregate sediment and nutrient contributions to any particular stream from a single event or over multiple years can degrade the integrity of downstream waters. There is strong evidence headwater streams function as nitrogen sources and sinks for river networks. Rapid nutrient cycling in small streams has the potential to remove 20-40% of N that might otherwise be exported downstream (USEPA 2015). Nitrogen and other nutrients can lead to over-enrichment of aquatic life and cause dissolved oxygen concentrations to fall below levels necessary to sustain most stream and streambed life. Nutrient overload (eutrophication) can have significant effects downstream (hypoxia).

The Sustainable Corn CAP team has examined water stress on crop production, drain flow in corn-based systems, and water quality under changing climate conditions. One practice referred to as controlled drainage shows potential to conserve some of the water that is "excess" in the spring, and hold it so it is available later in the year when crop growth is at its peak and soil moisture cannot keep up with crop water demand. This practice also has been studied as a way to reduce the nitrate loss into streams and rivers that has been linked to water quality problems downstream such as hypoxia in the Gulf of Mexico. Holding the water back allows water to flow through longer pathways, and seep into deeper soil layers.

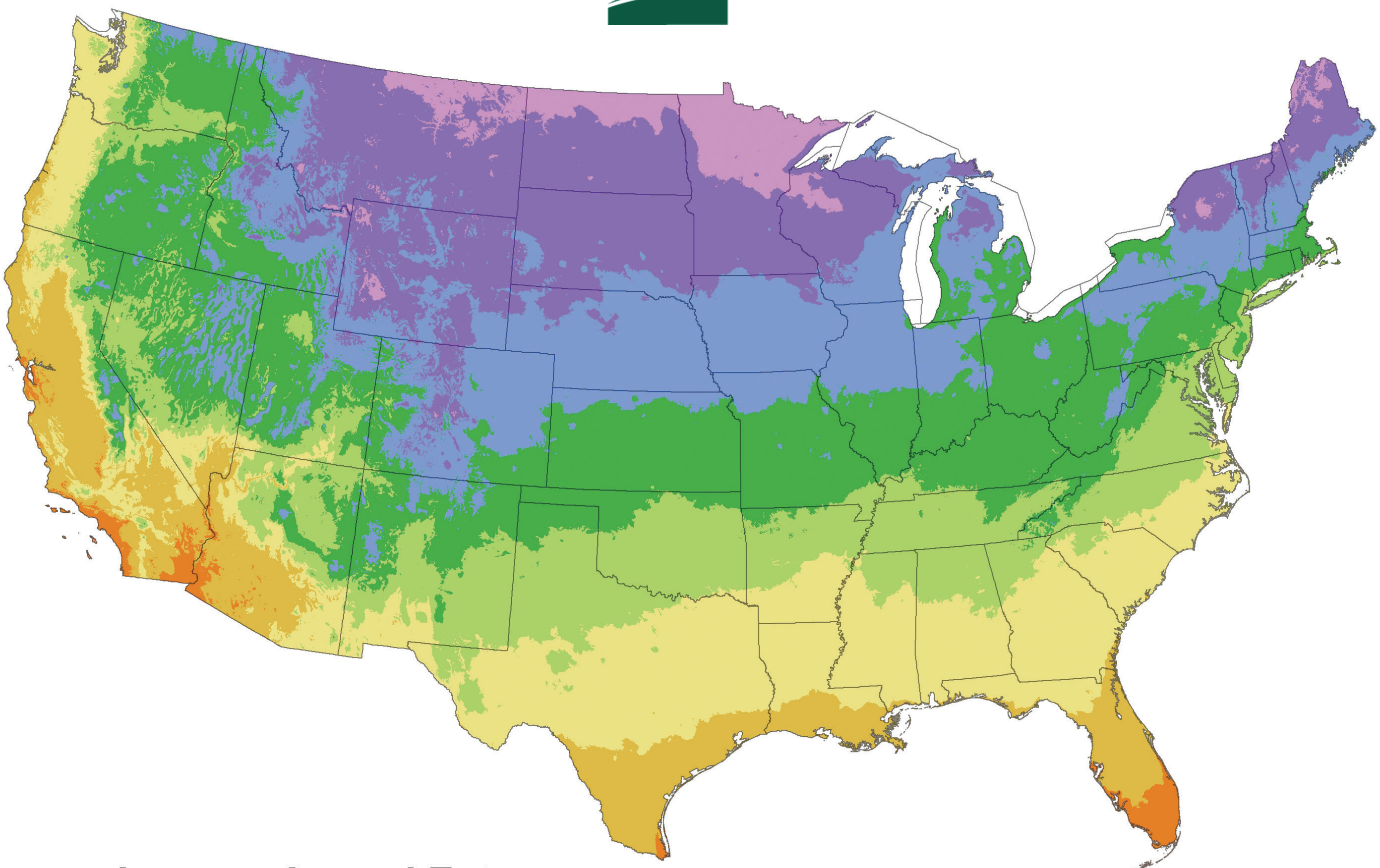
2.4.1 Water stress on crop production

Water use by crops is greatest at the time of their peak vegetative biomass, which occurs in July for corn and soybean grown in the upper Midwest. Sensitivity to excess water is not likely to occur during mid-season because of peak water consumption by the plants occurring. However, flooding still is possible as intensity of rainfall is an important factor. A shortage of water for crop use can happen throughout the growing season with detrimental effects on the yield potential of corn and soybean. Overall, corn is less resilient to water stress because of its determinate growth habit in which the plant flowers (silks) during a short period and severe moisture stress can hamper kernel fertilization. In contrast, soybean has a longer window of time of flowering because of its indeterminate growth habit. The overlap of the vegetative and reproductive growth in soybean allows for compensation by later flowers set by the plant if a period of water stress occurs.

Finding: Controlled drainage did not result in a statistically significant change in crop yield in any of the experimental sites across the Midwest region. Controlled drainage decreased the rate of water table recession by 29 to 62% in Indiana, increasing the time needed for the water table level to fall from the surface to 30 cm and 60 cm depth by approximately 12 to 26 and 24 to 53 hours, respectively.

FIGURE 4 | USDA Plant Hardiness Zone Map

USDA



Average Annual Extreme Minimum Temperature 1976-2005

Temp (F)	Zone	Temp (C)
-40 to -30	3	-40 to -34.4
-30 to -20	4	-34.4 to -28.9
-20 to -10	5	-28.9 to -23.3
-10 to 0	6	-23.3 to -17.8
0 to 10	7	-17.8 to -12.2
10 to 20	8	-12.2 to -6.7
20 to 30	9	-6.7 to -1.1
30 to 40	10	-1.1 to 4.4
40 to 50	11	4.4 to 10

Finding: The change in water table was not seen in Iowa, where outlet restriction may have masked this effect, or in Minnesota or Ohio where the water table did not rise near the surface during most growing seasons. However, the lack of an overall response in Minnesota is believed to be an artifact of the years in which the research was conducted, as these were drier compared to normal.

Implication: Controlled drainage should not be adopted primarily for yield benefits, but yield increases are possible, especially if timely rainfall events provide water for crop uptake and with active management of the outlet height. Lowering the outlet before storm events would reduce the amount of time the water table is at a level that could be detrimental to trafficability or crop yield.

Finding: Corn yield was correlated with soil moisture stress, particularly excess soil moisture stress or the absolute sum of excess and deficit stress.

Implication: Although soil moisture stress impacts yield, the impact of controlled drainage on soil moisture in most site-years is minimal. More research is needed on the yield reduction associated with excess moisture stress that may be associated with managing the controlled drainage outlet height too high, especially in specific crop development phases and on optimum strategies for managing the outlet.

Finding: Long-term implementation of highly productive continuous corn systems with all residues left after harvest improved soil water retention in the upper soil profile (at 0-10 and 10-20 cm depths) compared to corn-soybean and corn-soybean-wheat rotations in Wisconsin.

Implication: Changes in soil water retention may be observable among different cropping systems, however, the reasons for this difference are not clear. This may be a byproduct of lower inherent crop productivity from continuous corn compared to higher yielding rotations, and/or cooler and wetter soils from the thick residue cover.

2.4.2 Future climate and drain flow

Finding based on modeling: By late 21st century, subsurface drainage volume is projected to decrease in NW Ohio (Hardiness Zone 6; see Figure 4). This is primarily attributed to increased evaporation as a result of increased temperature. For a description of the model parameters used to generate this finding, refer to Appendix C.2.

Implication: Farmers in this eastern Corn Belt region are expected to begin developing irrigation strategies to meet growing season crop water requirements.

Recommendation: Farmers in NW Ohio should move forward aggressively to adopt controlled drainage and recycling systems to assist in managing water resources as a way to ensure adequate water for future cropping systems.

Finding based on modeling: Under future climate scenarios, controlled drainage is shown to offer similar reduction in drainage volume and nitrate load to streams as observed under current climate.

Implication: Controlled drainage is one of the most effective tools to reduce off-site delivery of nutrients carried in subsurface drainage water.

Recommendation: Educational and policy efforts that encourage farmer adoption and use of drainage water management principles, especially controlled drainage, can reduce nitrate loads to streams in the future.

Finding based on modeling: Subsurface drainage volume is expected to increase throughout the Corn Belt into mid-21st century with the greatest increase in Hardiness Zones 4 and 5. These increases largely are driven by decreases in frost depth and duration, resulting from increased temperature and a modest increase in precipitation. For description of models used to generate these findings, see Appendix C.3.

Implication: Farmers will continue to intensify subsurface drainage infrastructure in order to minimize excessive soil wetness. Greater drain flow may result in more overloading of county and district drainage systems, leading to longer times to drain the fields. Greater overall drain flow also would be expected to increase nitrate loads to receiving water bodies.

Implication: Farmers should incorporate drainage water management principles and infrastructure when designing and installing subsurface drainage systems.

Finding based on modeling: The proportion of drainage occurring before May 31 will increase

Graduate student Lindsay Pease, The Ohio State University, checks water quality collection equipment at an on-farm research site.

primarily in the more northern portions of the Corn Belt. An increase in percent winter drainage was simulated in USDA Hardiness Zones of:

• 2 to 14% increase in parts of zones 3, 4 and 5 (refer to Figure 4)

• 10 to 25% increase in the southern part of zone 4

• 0 to 5% increase in the southern part of zone 5 and all of zone 6

These projected increases are driven both by increases in winter precipitation of 10 to 14% across portions of zones 3-5 and 7 to 10% across zones 5-6, as well as decreases in frost depth. The northern portion of the region (zones 3-5) will experience a larger decrease in frost depth (15 to 23%) compared to the southern portion of the region (zones 5-6; 12 to 18%). Refer to Appendix C.4 for model parameters.

Implication: A greater proportion of drain flow occurring during the non-growing season may increase the ability of controlled drainage to reduce annual nitrate load.

Finding based on modeling: The depth of drain flow retained by controlled drainage will increase by 0 to 20 mm across most of the Corn Belt, but the percentage of annual drain flow retained with control drainage is essentially unchanged. Refer to Appendix C.4 for model parameters.

Implication: Controlled drainage can help mitigate the increase in drainage and associated nitrate load in the future, but it will not be able to reduce drainage by a greater proportion than it does currently.

2.4.3 Water quality under changing weather conditions

Finding based on modeling: Cropland contributes more than 70% of total N and 50% of P loads within the Upper Mississippi River Basin (UMRB) and Ohio-Tennessee River Basin (OTRB). Refer to Appendix C.5 for model parameters.

Implication: Agriculture is a key source of sediment and nutrient pollution to Corn Belt streams. The adoption of cover crops, no-till and other best management practices by farmers can reduce the losses of these pollutants based on scenario simulation results.

Finding based on modeling: Large sediment and nutrient reductions could occur for the UMRB and OTRB regions in response to widespread adoption of no-till, cover crops or extended rotations for both current baseline and future climate conditions. The effectiveness of no-till, extended rotations with alfalfa and a rye cover crop were similar in reducing sediment, total P, total N or nitrate for current climate conditions (1981 to 2010) versus future mid-century climate conditions (2046 to 2065). Refer to Appendix C.5 for model used.

Recommendation: Adoption of no-till, cover crops and/or extended rotations (with alfalfa or other integrated non-cash crops) should be pursued across the Corn Belt region to improve regional water quality and reduce the northern Gulf of Mexico hypoxic zone for both current and future climate conditions.

Finding based on modeling: Adoption of a rye cover crop on all land in corn-soybean production in the OTRB resulted in a reduction of total N that was nearly 20% greater under future mid-century (2046 to 2065) climate than the cover crop effects in response to current climate (1981 to 2010). Refer to Appendix C.5 for model used.

Implication: Under predicted future climate, nitrate loss to drainage water, N_2O emissions and soil loss are likely to increase relative to current conditions. Adding a cereal rye cover crop is expected to help lessen this loss but will not eliminate it entirely.

2.5 NITROGEN SYSTEM

The majority of N in soil systems is in organic compounds that are not available directly to plants and must be converted to ammonium and eventually nitrate (inorganic-N forms), or provided through biological symbiotic N fixation. Application of N fertilizer is a key input to corn production in the upper Midwest that complements biological N fixation (BNF) as well as microbial transformation of soil organic matter nitrogen to inorganic-N. The amount and rate of microbial transformation of soil organic matter (SOM)-N to inorganic-N is highly influenced by environmental conditions (e.g. temperature and precipitation). Thus, the requirement for supplementary N fertilizer application is highly variable from year-to-year and field-to-field.

Research by the Sustainable Corn CAP team has focused on better understanding the interaction between climate and the N cycle and how system diversification to include cover crops and inclusion of a third crop can impact N loss via nitrous oxide (greenhouse gas) and as nitrate leaching into water bodies.

2.5.1 Greenhouse gas: Nitrous oxide

Nitrogen fertilizer rate and weather are the two dominant factors affecting nitrous oxide (N_2O) emissions from corn fields. Although agriculture accounts for a relatively small proportion (approximately 8%; USEPA 2015) of total U.S. greenhouse gas (GHG) emissions, approximately two-thirds of emissions from the agricultural sector are due to N_2O that is emitted from nitrogen fertilizer applications. With a warming potential of about 300 times that of carbon dioxide (CO_2), nitrous oxide is among the most effective heat trapping gases in the atmosphere and therefore, of research importance. The Sustainable Corn CAP team was interested in how management may reduce N_2O emissions while being practical and implementable by farmers. Improvements can be made in several areas to reduce denitrification and nitrification that lead to N_2O emissions. If this is accomplished, emissions are likely to decrease in the current and potentially future climate.

Finding: Nitrous oxide (N_2O) emissions were reduced 60% by sensor-based N sidedress applications compared to standard pre-plant N management in Missouri. This reduction was due to delayed timing, since all N_2O reductions occurred during the period before sidedress N was applied.

Implication: Cost-share practices to encourage sidedress or split N applications will help to reduce N_2O emissions from corn, which is the biggest component of corn's greenhouse gas footprint.

Finding: N_2O emissions in Missouri were highly responsive to weather, and were much higher under very wet conditions in 2013-2015 and lower during drought in 2012.

Implication: N losses can be somewhat mitigated by improved weather prediction and application methods that increase nitrogen use efficiency. Continuing to develop strategies that better match fertilizer application rates with crop needs may reduce N_2O emission in the upper Midwest.

Finding: The use of specific management practices can avoid cover crop-induced increases in N_2O emissions. Mechanical termination and incorporation of cover crops into the soil tends to increase N_2O emissions by more than 150% compared to herbicide termination without incorporation into the soil.

PVC rings installed in a corn field. Greenhouse gas (GHG) collection chambers are placed onto the rings to take GHG measurements.

Implication: The impact of cover crops on nitrate loss may reduce downstream N_2O emissions. Cover crops should be managed for these benefits, while also considering practices that minimize N_2O emissions, such as using herbicides for termination without incorporation into the soil.

Finding: Legume cover crops tend to increase N_2O emissions after termination and during decomposition, but have less N_2O emissions while the cover crop is growing. When N_2O emissions are monitored year-round, the effect of cover crops (legumes, grasses or mixtures) on N_2O is close to zero.

Implication: Monitoring N_2O emissions in late fall and winter is important when comparing systems affected by time, such as with and without cover crops, despite their potential small effect on total annual N_2O emissions.

Finding based on modeling: Model studies indicate a cereal rye cover crop provides substantial environmental benefits in a corn-soybean rotation by reducing nitrate loss to drainage water, nitrous oxide emissions and soil loss across the Midwest region, without significant yield loss.

Implication: Under predicted future climate, a cereal rye cover crop is expected to yield larger reductions in nitrate loss to drainage water, N_2O emissions and soil loss relative to current conditions.

2.5.2 Nitrogen fertilizer applications

Research conducted in Missouri and Ohio compared standard pre-plant application of nitrogen fertilizer at a fixed rate to variable-rate sidedress nitrogen using crop sensors installed on fertilizer applicators. These practices need continued research efforts to account for a wider spectrum of variables affecting nitrogen use efficiency for the crop and system as a whole. An integrated approach needs to be continued with emphasis on soil type, crop rotation, and interaction with weather.

Finding: Sensor-based N side dressing gave the highest yields in Missouri while lowering nitrogen use, but under-recommended N applications in Ohio; sensor height above the crop is hypothesized to account for differences in findings. See Appendix C.6 for equipment application details.

Implication: Sensor-based N side dressing has the potential to produce both production and environmental benefits, but needs additional development to produce these benefits reliably.

Implication: Total N off-field, off-farm loss as nitrate and N_2O is anticipated to increase under future climate scenarios. Split-applications of N have potential to be an important management tool to maintain yield and limit N loss that may result from increased amounts and intensity of spring rainfall.

SENSORS

Optimal nitrogen fertilizer rate varies widely within a field. Using equipment to sense nitrogen needs in the corn canopy while applying N fertilizer is a promising approach to diagnose and treat the variation in real time. Two sensors are mounted on either side of the tractor, in front. A computer in the cab reads the sensors, calculates N rate and directs the controller to apply a particular rate of fertilizer.

FIGURE 5 | Relationship between percent soil organic carbon (SOC) and corn grain yield, 2011-2015.

Data are presented here on the plot-level from 23 Sustainable Corn CAP research sites in 8 states. The inherent productivity of corn is related to a soil's carbon content with an upward trend in yield as SOC increases. Variation in SOC within and across states is one factor influencing crop yields with weather and management as additional factors. Strategies that aim to increase a soil's carbon content is a valuable, long-term investment especially when paired with other conservation practices.

2.6 CARBON SYSTEM

Changes in soil organic carbon (SOC) content are slow to become evident in the short time frame of this project (2011 to 2015). An increase in SOC content, which is the goal of C sequestration, also is difficult in annual cropping systems with significant difference occurring in sequestration potential across the region. Continued focus and priority placed on soil conservation and improving soil quality/health are critical for land stewardship and long-term productivity. Increased SOC content in the soil results in many benefits such as increased water retention and nutrient cycling. Higher SOC content results in higher crop yields (see Figure 5), which is another motivating factor for farmers to place priority on this.

Finding: The SOC content across experimental sites tended to be influenced more by tillage practice than by cover crop or N management. No-till management helped to maintain soil C in a corn-soybean system, but when tilled the soil C declined, although erosion may have been a contributor to this decline.

Implication: Eliminating tillage is an important step in maintaining the existing SOC content of a soil when other management practices are held constant.

Finding: Four years of cereal rye cover crop integrated into a corn-soybean system did not significantly increase SOC at most of the cover crop sites across the region.

Implication: Although cover crops are known to add additional C back to the soil, this is a long-term investment. Based on project experiments, more than four years of cereal rye cover crops are necessary before a significant increase in SOC becomes measurable.

Finding: Four years of cereal rye cover crop did not significantly affect soil bulk density or soil water retention curves at most of the cover crop sites across the region.

Implication: Soil physical properties such as bulk density and water retention curves are slow to change, and cover crops are not likely to significantly impact these properties over the short term.

Finding: In Indiana, there was greater cereal rye cover crop biomass in general compared to other Sustainable Corn CAP research sites because of more favorable weather conditions for growth. After four years of cereal rye cover crop at the Indiana site, the wet soil aggregate stability was significantly greater in the top 20 cm (8 inches) of a silt loam soil.

Implication: Cover crops can improve soil structure, which can lead to reduced soil crusting and erosion and increased water infiltration with time.

Finding: Analysis of in-depth farmer interviews identified an emergent construct of a "soil stewardship ethic" that helps explain why and how some farmers are actively enhancing their soil resources as a way to adapt to more variable and extreme weather. Farmers who articulated this soil stewardship ethic were attempting to shift from short-term reactivity to seasonal weather variability toward intentional management of their soil resources to build longer-term resilience of their farm operations. In other words, farmers' soil stewardship ethics appear to be helping them bridge short-term profit imperatives and long-term sustainability goals (Roesch-McNally et al. In revision).

Finding: This research provided empirical evidence the increased emphasis that agencies and organizations such as the USDA NRCS and the United Nations are placing on soils and soil health is resonating with farmers, and is likely to continue to be well-received by Corn Belt farmers (Roesch-McNally et al, (in revision)).

Implication: Engaging farmers in conversations about soil stewardship may be an effective way to encourage them to adopt conservation practices, particularly if the practices both build soil health and help to reduce weather-related risks on their farm.

Recommendation: Further research is needed on farmers' soil stewardship ethics, and how better understanding of soil stewardship ethics can be integrated into climate risk reduction efforts.

Recommendation: Interdisciplinary research opportunities should engage farmers in field-level research to assess whether farmers who express attitudes associated with the soil stewardship ethic are actually improving soil resources on their farms through the adoption and use of conservation practices.

SECTION 3. CONCLUSIONS

Realizing the potential of corn-based cropping systems to meet the food, feed, fuel, and fiber needs of a growing global population under changing climatic conditions will require the integration of advanced genetics (G), better understanding of the environment (E), and knowledge and motivation to manage differently (M) (Hatfield and Walthall. 2015). The research of the Sustainable Corn CAP informs the interactions among E x M to better understand the nitrogen, carbon, and water cycles and their systems relationships.

Field experimentation, statistical models, and biophysical models point to the effects that variability in weather-climate and farmer management practices have on crop yield, water use efficiency, beneficial and harmful insects, sediment and nitrate loads, soil water retention, and nitrous oxide (N_20) emissions. Cover crops, no-till, and controlled drainage show promise in improving components of the N, C, and water cycles, but are not sufficient alone to stabilize and increase yields while solving unintended environmental concerns associated with cultivated systems. Project findings reinforce there are no single or simple solutions to improving yields under changing climate, while simultaneously protecting and managing water resources, reducing off-field, off-farm N loss, retaining and enhancing soil carbon stocks, and ensuring farm livelihoods.

Management is a critical factor in realizing the full potential of the corn-based system and must not be treated as a "black box" variable in the G x E x M analysis. Studying the biophysical impacts differing management practices have, in addition to social science research regarding factors associated with human management decision-making under variable conditions, allows validation of assumptions and development of a robust structure for understanding G x E x M system interactions. It is essential individual and public policy-level decisions are based on data and models that incorporate the impacts of a suite of management practices and the capability and willingness of land managers and farmers to tailor practices to their own unique situations. There are many constraints to co-producing high quality crops with increasing grain yields and essential soil, water and other ecosystem services agriculture and society needs now and in the future (Hatfield and Walthall 2015). Future research must continue to push the boundaries of system-level science and engage transdisciplinary teams, if these constraints are to be understood and overcome.

This multi-state and transdisciplinary Sustainable Corn CAP project advanced biophysical and social-economic research in the discovery of scientifically proven field, farm, and landscape level results for dual benefits to the farm enterprise and the environment. These goals are not in opposition and the discoveries from this project will continue to pave the agriculture scientific frontier as we seek to improve the resiliency and sustainability of our main production systems in the upper Midwest. Those directly involved in farming and those who act as consumers in the agricultural value chain are mutually interested in sustainability, resiliency, and the long-term assurance of safe and affordable sources of food, feed, fiber, and fuel. The Sustainable Corn CAP research findings presented in Volume 1 and Volume 2 summarize major outcomes from this five-year project during the 2011-2016 grant period. These volumes are only a snapshot of project findings. Although this project officially ended February 28, 2017, we anticipate analyses and simulations based on project data will continue with results published several years into the future.

SECTION 4. SUPPORTING SCIENTIFIC PUBLICATIONS

Refereed Journals

Refereed Journals not included in Volume 1 are listed below. All graduate dissertations and theses are listed here for the entire project.

Arbuckle, J.G., J. Hobbs, A. Loy, L.W. Morton, L. Prokopy and J. Tyndall. 2014. Understanding Corn Belt farmer perspectives on climate change to inform engagement strategies for adaptation and mitigation. Journal of Soil and Water Conservation, Special Issue for Climate and Agriculture. 69(6):505-516. http://dx.doi.org/10.2489/jswc.69.6.505

Arbuckle, J.G., J. Tyndall, L.W. Morton and J. Hobbs. 2017. Climate change typologies and audience segmentation among Corn Belt farmers. Journal of Soil and Water Conservation, Special Issue on Sustainable Corn Production Systems. 72(3): 230-239.

Bailey, R.R., T.R. Butts, J.G. Lauer, C.A.M. Laboski, C.J. Kucharik and V.M. Davis. 2015. Effect of weed management strategy and row width on nitrous oxide emissions in soybean. Weed Science. 63(4):962-971. http://dx.doi.org/10.1614/WS-D-15-00010.1

Barker, D. and J. Sawyer. 2017. Variable rate N management in corn: Response in two crop rotations. Journal of Soil and Water Conservation, Special Issue on Sustainable Corn Production Systems. 72(3): 183-190.

Basche, A.D. and G.E. Roesch-McNally. 2017. Research topics to scale up cover crop use: Reflections from innovative Iowa farmers. Journal of Soil and Water Conservation, Special Issue on Sustainable Corn Production Systems. 72(3): 59A-64A.

Beehler, J., J. Fry, W. Negassa and A.N. Kravchenko. 2017. Impact of cover crop on soil carbon accrual in topographically diverse terrain. Journal of Soil and Water Conservation, Special Issue on Sustainable Corn Production Systems. 72(3): 272-279.

Dunbar, M., A. Gassmann and M. O'Neal. 2016. Impacts of rotation schemes on ground-dwelling beneficial arthropods. Environmental Entomology. 1-7. http://dx.doi.org/10.1093/ee/nvw104

Fry, J., A.K. Guber, M. Ladoni, J.D. Munoz and A.N. Kravchenko. 2016. The effect of up-scaling soil properties and model parameters on predictive accuracy of DSSAT crop simulation model under variable weather conditions. Geoderma. 287:105-115. http://dx.doi.org/10.1016/j.geoderma.2016.08.012

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SECTION 5. PROJECT PRINCIPAL INVESTIGATORS

Lois Wright Morton, project director and professor, Iowa State University

Lori J. Abendroth, project manager, Iowa State University

Robert Anex, professor, University of Wisconsin

J. Gordon Arbuckle, Jr., associate professor, Iowa State University

Raymond W. Arritt, professor, Iowa State University

Bruno Basso, professor, Michigan State University

Jamie Benning, extension program manager, Iowa State University

Laura Bowling, associate professor, Purdue University

Michael Castellano, associate professor, Iowa State University

Joe P. Colletti, senior associate dean, Ag & Life Sciences; director, Experiment Station, Iowa State University

Richard M. Cruse, professor, Iowa State University, director, Iowa Water Center

Warren A. Dick, professor, The Ohio State University

Norman Fausey, research leader and soil scientist, USDA-ARS, Columbus, Ohio

Jane Frankenberger, professor, Purdue University

Philip Gassman, associate scientist, Iowa State University

Aaron J. Gassmann, associate professor, Iowa State University

Matthew Helmers, professor, Iowa State University

Daryl Herzmann, systems administrator and analyst, Iowa State University

Chad G. Ingels, extension program specialist, Iowa State University

Eileen J. Kladivko, professor, Purdue University

Catherine L. Kling, distinguished professor, Iowa State University

Sasha Kravchenko, professor, Michigan State University

Rattan Lal, distinguished university professor, The Ohio State University

Joseph G. Lauer, professor, University of Wisconsin

Kristi Lekies, associate professor, The Ohio State University

Fernando E. Miguez, assistant professor, Iowa State University

William (Wade) Miller, professor, Iowa State University

Richard H. Moore, professor, The Ohio State University

Daren S. Mueller, assistant professor, Iowa State University

Emerson D. Nafziger, professor, University of Illinois

Nsalambi Nkongolo, professor, Lincoln University

Matthew O'Neal, associate professor, Iowa State University

Lloyd Owens, research soil scientist, USDA-ARS

Phillip Owens, associate professor, Purdue University

John E. Sawyer, professor, Iowa State University

Peter Scharf, professor, University of Missouri

Martin Shipitalo, research soil scientist, USDA-ARS

Jeffrey S. Strock, professor, University of Minnesota

Dennis Todey, associate professor and state climatologist, South Dakota State University

John Tyndall, associate professor, Iowa State University

Maria B. Villamil, assistant professor, University of Illinois

SECTION 6. RESEARCH PERSONNEL INCLUDING POST-DOCTORAL ASSOCIATES, GRADUATE STUDENTS AND RESEARCH STAFF

Postdoctoral Research Associates

Landon Bunderson, Agronomy, Iowa State University (2013-15)

Aaron Daigh, Agricultural and Biosystems Engineering, Iowa State University (2013)

Benjamin Dumont, Geological Sciences, Michigan State University (2015-16)

Andi Hodraj, Agricultural and Biological Engineering, Purdue University (2016)

Javed Iqbal, Agronomy, Iowa State University (2011-16)

Maria Gonzales-Ramirez, Economics, Iowa State University (2015-16)

Sandeep Kumar, School of Environment and Natural Resources, The Ohio State University (2011-12)

Ainis Lagzdins, Agricultural and Biosystems Engineering, Iowa State University (2014-16)

Ruiqiang Liu, School of Environment & Natural Resources, The Ohio State University (2014-16)

Suresh Lokhande, Sociology, Iowa State University (2014-2016)

Atanu Mukherjee, School of Environment and Natural Resources, The Ohio State University (2013-15)

Toru Nakajima, School of Environment and Natural Resources, The Ohio State University (2012-14)

Magdalena Necpalova, Biological Systems Engineering, University of Wisconsin (2013-14)

Wakene Negassa Chewaka, Plant, Soil and Microbial Sciences, Michigan State University (2011-14)

Vincent Obade, School of Environment and Natural Resources, The Ohio State University (2012-15)

Ioannis Panagopoulos, Center for Agricultural and Rural Development, Iowa State University (2012-13)

Jose Pantoja, Agronomy, Iowa State University (2011-13)

Rashid Rafique, Biological Systems Engineering, University of Wisconsin (2011-12)

Ehsan Toosi, Plant, Soil and Microbial Sciences, Michigan State University (2014-16)

Adriana Valcu-Lisman, Economics, Iowa State University (2013-16)

Yongjie Yi, Center for Agricultural and Rural Development, Iowa State University (2013-15)

Ph.D. Students

Grazieli Araldi da Silva, Plant Pathology & Microbiology, Iowa State University (2014-16)

Jenette Ashtekar, Agronomy, Purdue University (2011-14)

Andrea Basche, Agronomy, Iowa State University (2011-15)

Chun-mei Chiu, Agronomy, Purdue University (2013)

Shashi Dhungel, Biological Systems Engineering, University of Wisconsin (2011-13)

Mike Dunbar, Entomology, Iowa State University (2011-16)

Jessica Fry, Plant, Soil and Microbial Sciences, Michigan State University (2014-16)

Syed Maaz Gardezi, Sociology, Iowa State University (2014-17)

Maria Gonzalez-Ramirez, Economics, Iowa State University (2011-15)

Lei Gu, Biological Systems Engineering, University of Wisconsin (2014-16)

Samuel Haruna, Agriculture and Environmental Science, Lincoln University and University of Missouri (2013-16)

Jonathan Hobbs, Sociology, Iowa State University (2012-13)

Maciej Kazula, Agronomy, University of Wisconsin (2011-16)

Moslem Ladoni, Plant, Soil and Microbial Sciences, Michigan State University (2011-15)

Charlotte Lee, Agronomy, Purdue University (2016-17)

Scott Lee, Agronomy, Iowa State University (2011-15)

Adam Loy, Sociology, Iowa State University (2012-13)

Guillermo Marcillo, Agronomy, Iowa State University (2014-17)

Jean McGuire, Sociology, Iowa State University (2011-14)

Juan Munoz, Plant, Soil and Microbial Sciences, Michigan State University (2011-14)

Ryan Nagelkirk, Geological Sciences, Michigan State University (2013-15)

Lindsay Pease, School of Environment and Natural Resources, The Ohio State University (2012-16)

Michelle Quigley, Plant, Soil and Microbial Sciences, Michigan State University (2013-16)

Gabrielle Roesch-McNally, Sociology, Iowa State University (2012-16)

Samane Saadat, Agricultural and Biological Engineering, Purdue University (2014-16)

Erin Seldat Kline, Agricultural and Biosystems Engineering, South Dakota State University (2012)

Aditi Sengupta, School of Environment and Natural Resources, The Ohio State University (2013-15)

Timothy Sklenar, Agronomy, Iowa State University (2015-16)

Emma Snyder, School of Environment and Natural Resources, The Ohio State University (2014-16)

Maninder Walia, School of Environment and Natural Resources, The Ohio State University (2013-15)

Adam Wilke, Sociology, Iowa State University (2014-16)

Lu Zhang, Bioproducts and Biosystems Engineering, University of Minnesota (2014-17)

Stacy Zuber, Crop Sciences, University of Illinois (2013-16)

Note:

Adam Wilke, Lei Gu, Stacy Zuber and Samuel Haruna have dual degrees (current PhD and past MS). Likewise, Jose Pantoja and Adriana Valcu-Lisman worked as postdoctoral associates and were also PhD students with the project. These individuals are listed only once here.

M.S. Students

Shanta Acharya, Agriculture and Environmental Science, Lincoln University (2014-16)

Balogun Afolasade, Agriculture and Environmental Science, Lincoln University (2015-16)

Hasan Ali, Agriculture and Environmental Science, Lincoln University (2013-15)

Rebecca Bailey, Agronomy, University of Wisconsin (2012-15)

Jordan Beehler, Plant, Soil and Microbial Sciences, Michigan State University (2015-17)

Kyle Brooks, Agricultural and Biological Engineering, Purdue University (2011-13)

Brittany Campbell, School of Environment and Natural Resources, The Ohio State University (2011-12)

Jason Cavadini, Agronomy, Purdue University (2011-13)

Kristina Craft, Agricultural and Biosystems Engineering, Iowa State University (2014-16)

Ariele Daniel, Agronomy, Iowa State University (2014-15)

Omar de Kok-Mercado, Agronomy, Iowa State University (2013-14)

Christopher Eidson, School of Environment and Natural Resources, The Ohio State University (2013-15)

Trevor Frank, Agronomy, Purdue University (2013-15)

Laura Frescoln, Sociology, Iowa State University (2013-15)

Ryan Goeken, Agricultural and Biosystems Engineering, Iowa State University (2011-13)

Gang Han, Plant Pathology and Microbiology, Iowa State University (2012-14)

Kaylissa Horton, Agronomy, Purdue University (2011-13)

Caroline Hughes, Agricultural and Biological Engineering, Purdue University (2014-16)

Anna Johnson, Sociology, Iowa State University (2014-16)

Reed Johnson, School of Environment and Natural Resources, The Ohio State University (2014-16)

Natalie Jozik, Biological Systems Engineering, University of Wisconsin (2014-16)

Renan Kobayashi Leonel, Plant Pathology and Microbiology, Iowa State University (2014-16)

Guy Bou Lahdou, Agricultural and Biological Engineering, Purdue University (2013-14)

Ao Li, Biological Systems Engineering, University of Wisconsin (2011-13)

Amanda Locker, Agricultural and Biological Engineering, Purdue University (2016)

Ellen Maas, School of Environment and Natural Resources, The Ohio State University (2015-17)

Scott Mayhew, School of Environment and Natural Resources, The Ohio State University (2014)

Brandon Mebruer, Agriculture & Environmental Science, Lincoln University (2011-12)

David Mitchell, Agronomy, Iowa State University (2010-12)

Dinesh Panday, Agriculture and Environmental Science, Lincoln University (2013-15)

Swetabh Patel, Agronomy, Iowa State University (2013-16)

Richard Price, Plant, Soil and Microbial Sciences, Michigan State University (2013-16)

Dipti Rai, Agriculture and Environmental Science, Lincoln University (2014-16)

Rebecca Roberts, Agronomy, Iowa State University (2013-15)

Joseph Rorick, Agronomy, Purdue University (2014-16)

Stephanie Sale, Agriculture and Environmental Science, Lincoln University (2011-13)

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Appendix A

Abbreviations and acronyms used in this report.

BMP	Best management practice
BNF	Biological nitrogen fixation
C	Carbon
CO_2	Carbon dioxide
GCM	General circulation models
GFDL	Geophysical Fluid Dynamics Laboratory Model
HadCM3	Hadley Center Model
HUC	Hydrologic unit code
IPCC	Intergovernmental Panel on Climate Change
MRTN	Maximum return to nitrogen
N	Nitrogen
N_2O	Nitrous Oxide
NASS	National Agricultural Statistics Service
NOAA	National Oceanic and Atmospheric Administration
NT	No-tillage
ORTB	Ohio-Tennessee River Basin
P	Phosphorus
PCM	Parallel climate model
SOC	Soil organic carbon
SOM	Soil organic matter
SWAT	Soil and water assessment tool
UMRB	Upper Mississippi River Basin

Appendix B

Institutional research farms with one or more experimental plots as part of the team research

Agricultural Drainage Water Quality–Research and Demonstration Site, Iowa State University

Agricultural Engineering and Agronomy Research Farms, Iowa State University

Arlington Agricultural Research Station, University of Wisconsin

Bradford Research and Extension Center, University of Missouri

Davis Purdue Agricultural Center, Purdue University

Freeman Farm, Lincoln University

Hicks Farm, Southwest Research and Outreach Center, University of Minnesota

Lancaster Agricultural Research Station, University of Wisconsin

Marshfield Agricultural Research Station, University of Wisconsin

Michigan State University Agronomy Farm: Mason Research Farm

North Appalachian Experimental Watershed Agricultural Research Station, USDA-ARS, Coshocton, Ohio

Northwest Agricultural Research Station, The Ohio State University

Northwestern Illinois Agricultural Research and Demonstration Center, University of Illinois

Ohio Agricultural Research and Development Center, The Ohio State University

On-farm DWM site in Pusheta Creek watershed, Clay Township, Auglaize County, OH, The Ohio State University

Orr Agricultural Research and Demonstration Center, University of Illinois

Southeast Purdue Agricultural Center, Purdue University

Southeast Research and Demonstration Farm, Iowa State University

Variable Input Crop Management Study, University of Minnesota

Waterman Agricultural and Natural Resources Laboratory, The Ohio State University

W.K. Kellogg Biological Station, Michigan State University

Appendix C

Descriptions of models used and research details referenced within main text

Appendix C.1.

Name, institutional information, country of origin, grid spacing, and ECS and TCR data for the seven global circulation models (GCMs) used for the OTRB climate change analyses@@.

Model	Institution	Country	Grid spacing##	ECS (TCR)%%
BCCR-BCM2.0	Bjerknes Centre for Climate Research	Norway	T63 (1.9º x 1.9º)	Na
CGCM3.1	Canadian Centre for Climate Modelling and Analysis	Canada	T47 (2.5º x 2.5º)	3.4 (1.9)
CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques	France	T63 (1.9º x 1.9º)	Na(1.6)
INM-CM3.0	Institute for Numerical Mathematics	Russia	4º x 5º	2.1 (1.6)
IPSL-CM4	Institut Pierre Simon Laplace	France	2.5º x 3.75º	4.4 (2.1)
MIROC3.2 (medres)	University of Tokyo, National Institute for Environmental Studies, and Frontier Research Center for Global Change	Japan	T42 (2.8º x 2.8º)	4.0 (2.1)
MRI-CGCM2.3.2	Meteorological Research Institute		T42 (2.8º x 2.8º)	3.2 (2.2)

@@See Panagopoulos et al. (2015) within the Endnotes section of this document for further description of these GCMs.

##Grid spacing is the latitude-by-longitude spacing of the computational grid, or the spectral truncation and near-equatorial latitude-by-longitude spacing of the corresponding Gaussian grid for spectral models.

%%ECS and TCR are equilibrium climate sensitivity and transient climate response in units of K, with “na” indicating values are not available.

Appendix C continued....

Descriptions of models used and research details referenced within main text

Appendix C.2.

For the finding described on page 16, this was based on specific modeling parameters:

This study used the DRAINMOD hydrologic model to simulate subsurface drainage discharge at a field site in the headwaters of the Western Lake Erie Basin using future climate patterns projected by 20 general circulation models (see table below). All of the available GCMs from Phase Five of the Coupled Model Intercomparison Project (CMIP5) that had been downscaled for the contiguous United States were employed. Downscaled projections were obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections (Maurer et al. 2007). Projections were bias-corrected and statistically downscaled to a daily time scale and to 1/8° spatial resolution (about 140 square kilometers per grid cell) using the Bias-Correction Constructed Analogues (BCCA) method (Bureau of Reclamation 2013). The grid cell used in this study was centered at 40° 33' 45" N, 84° 3' 45" W. This study examined changes in the agricultural water balance under two future radiative forcing scenarios known as representative concentration pathways (RCPs). RCP 4.5 represents a climate scenario in which global population stabilizes at nine billion, and global emissions reduction policies lead to a peak in GHG emissions by 2050 with a decline to stable levels by 2080. RCP 8.5 represents a "business as usual" climate scenario in which global population increases to 12 billion by 2100 with no significant global climate policies to reduce GHG emissions (Moss et al. 2008). Using this method, 19 and 20 GCMs were available for RCP 4.5 and 8.5, respectively.

Table. Coupled Model Intercomparison Project Phase 5 General Circulation Models used to simulate future changes in climate for Northwest Ohio.

Model Name	Model Center (or Group)
ACCESS1.3	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration
CanESM2	Canadian Centre for Climate Modelling and Analysis
CCSM4	National Center for Atmospheric Research
CESM1(CAM5)	Community Earth System Model Contributors
CNRM-CM5	Centre National de Recherches Météorolgiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) in collaboration with Queensland Climate Change Centre of Excellence
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory
INM-CM4	Institute for Numerical Mathematics
IPSL-CM5A-LR	Institute Pierre-Simon Laplace

Model Name	Model Center (or Group)
IPSL-CM5A-MR	Institute Pierre-Simon Laplace
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MPI-ESM-LR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)
MPI-ESM-MR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)
MRI-CGCM3	Meteorological Research Institute
NorESM-M	Norwegian Climate Centre

Appendix C.3.

For the finding described on page 16, this was based on specific modeling parameters:

The simulations were driven by meteorological data from three climate models (Parallel Climate Model (PCM), the Hadley Center Model (HadCM3) and the Geophysical Fluid Dynamics Laboratory model (GFDL)) using two different greenhouse gas emissions scenarios as defined by the Special Report on Emissions Scenarios. The A2 scenario describes a greater increase in greenhouse gas emissions by mid-century associated with a continuously growing world population, while the B1 scenario represents moderate increases in total emissions by mid-century. These increases are largely driven by increases in winter and annual precipitation. Simulations based on the A1B emissions scenario which represents balanced energy use and total emissions in between the other two scenarios by mid-century predict decreases in annual drainage in parts of Minnesota.

Appendix C.4.

For the finding described on page 17, this was based on specific modeling parameters:

The findings are based on the average of simulations driven by meteorological data for the A1B emissions scenario from one climate model (PCM).

Appendix C.5.

For the findings described on page 17, these were based on specific modeling parameters:

This finding is based on baseline Soil and Water Assessment Tool (SWAT) simulation results for the two regions: Upper Mississippi River Basin (UMRB) and Ohio-Tennessee River Basin (OTRB).

Appendix C.6.

For the finding described on page 19, this was based on nitrogen sensors placed on tractors that are above the crop. Sensor height is the most likely explanation for the difference in performance between the nitrogen fertilizer recommendations for the two states. Sensors were 50 cm above plants in Missouri, but 80 cm above plants in Ohio; the latter was likely too far away from plants to distinguish their N status.

The Climate and Corn-based Cropping Systems CAP (Sustainable Corn CAP) is a USDA-NIFA supported program, Award No. 2011-68002-30190. It is a transdisciplinary partnership among 11 institutions creating new science and educational opportunities. The Sustainable Corn CAP seeks to increase resilience and adaptability of Midwest agriculture to more volatile weather patterns by identifying farmer practices and policies that increase sustainability while meeting crop demand.

SUSTAINABLE CORN.ORG
CROPS, CLIMATE, CULTURE AND CHANGE

USDA United States Department of Agriculture | National Institute of Food and Agriculture

Participating Institutions

Agricultural Research Service
Iowa State University
Lincoln University
Michigan State University
The Ohio State University
Purdue University
SDSU South Dakota State University
Illinois
University of Minnesota Driven to Discover
University of Missouri
Wisconsin University of Wisconsin–Madison

Useful to usable

A portion of the socioeconomic research findings were from a joint survey conducted in partnership with Useful to Usable (U2U): Transforming Climate Variability and Change Information for Cereal Crop Producers (Award No. 2011-68002-30220).

Additional funding was provided by these partners to expand the scope and reach of research by the Sustainable Corn CAP team.

USB United Soybean Board
USDA United States Department of Agriculture Natural Resources Conservation Service
Annie's
Farmers Advocating for Organics
Sustainable Food Trade Association
Organic Valley